the diffusion will never reach beyond certain limits. During unstable stratification the eddies travel with increasing velocity toward infinity.

Finally the equation for $E$ is combined with the equation for eddy convection of heat, and an integral is derived which gives the simultaneous changes in $E$ and $\theta$ (the potential temperature) when two infinitely thick adiabatic air layers are separated by a thin superadiabatic layer and overturning sets in. The solution is applied to the discussion of the cause of certain thunderstorms.

(3) Under the assumption that close to the ground the large eddies of the free atmosphere are rapidly annihilated, it is found that $E$ here must be proportional to $\sqrt{h}$.

(4) This boundary condition is used for deriving a stationary distribution of $E$ in a limited atmosphere. Since $E$ and the eddy viscosity are proportional, the resulting curve for $E$ can be compared with known values of the variation of eddy viscosity with height and fair agreement is found.

ACKNOWLEDGMENTS

In carrying out this study the author has had the benefit of numerous suggestions from Prof. W. J. Humphreys and Mr. E. A. Woolard of the United States Weather Bureau, as well as from Dr. H. U. Sverdrup, Bergen, Norway, for which he wishes to express his sincere gratitude. Thanks are also due to Dr. B. M. Varney, of the Weather Bureau, who has carefully revised the manuscript from a linguistic point of view.

LITERATURE CITED

(1) SOLBERG, H.
1923. SUR LE FROTTEMENT DANS LES COUCHES BASSES DE L'ATMOSPHÈRE. Förh. vid Skand. Naturf. Mötet i Göteborg, p. 95.

(2) ROSSBY, C.-G.
1924. ON THE ORIGIN OF TRAVELLING DISCONTINUITIES IN THE ATMOSPHERE. Geografiska Annaler, vol. 6, p. 180.

(3) RICHARDSON, L. F.
1920. THE SUPPLY OF ENERGY TO AND FROM ATMOSPHERIC EDDIES. Proceedings of the Royal Society, A. Vol. 97, p. 354.

(4) 1913. BULLETIN OF THE MOUNT WEATHER OBSERVATORY. Vol. 6, p. 246.

(5) HUMPHREYS, W. J.
1920. PHYSICS OF THE AIR, p. 347, Philadelphia.

(6) ROBITZSCH, M.
1917. BEITRÄGE ZUR KENNTNISS DER STRUKTUR DES BODENWINDES. Arbeiten des Königlich Preussischen Aeronautischen Observatoriums bei Lindenberg, p. 90.

# A FURTHER STUDY OF EFFECTIVE RAINFALL

551.578.1 : 633

By J. F. VOORHEES

[Weather Bureau, Honolulu, Hawaii]

With every new attempt to find a correlation between rainfall and the growth or yield of some crop one is more deeply impressed with the need for further information concerning effective rainfall and the factors which determine how large a proportion of a given amount of precipitation may be utilized. The problem has been attacked, directly or indirectly, by many investigators and from several angles, but we still have no information that is definite enough to make a satisfactory basis for a correlation between precipitation and yield. Yet we get apparently high correlations in many instances. For example, the correlation coefficient between June rainfall and the yield of oats at Akron, Colo., as calculated by Mr. Mattice, of this bureau, is $+0.91 \pm 0.03$. This is thirty times the probable error but when we try to discover just what this high correlation is good for we find it worth very little indeed. If yields are calculated by the least square formula $y' = bx + a$, the standard deviation of $y - y'$ is found to be 59 per cent less than the standard deviation of $y$. But the departure of $y'$ from $y$ was 75 per cent of the mean value of $y$ one-fifth of the time, which would make our calculated yield little if any better than a good guess, and practically worthless for predicting yields.

The amount of water used in making a crop of corn has been so often determined and the results are in such close agreement that we may feel reasonably certain that each pound of dry matter in a corn plant will have used from 250 to 400 pounds of water, depending on the fertility of the soil. The larger amount will have been used on the poorer soil. Thus, after it has been harvested and weighed, we can tell about how much water a given crop has used.

It has been shown also that the application of manure or of a straw mulch will increase the moisture-holding capacity of most soils, and measurements have been made of the amount of water available in the upper layers of various soils when saturated. Here, again, we have nothing on which a forecast could be based.

In a previous paper (this REVIEW, February, 1925) the writer attempted to determine the amount of effective rainfall by a process of elimination. First, there was deducted a minimum amount which it was assumed would be lost by immediate evaporation after each rain. Second there was deducted the amount discharged in the streams, as evidently having been of no benefit, whether or not it might have been beneficial under different conditions.

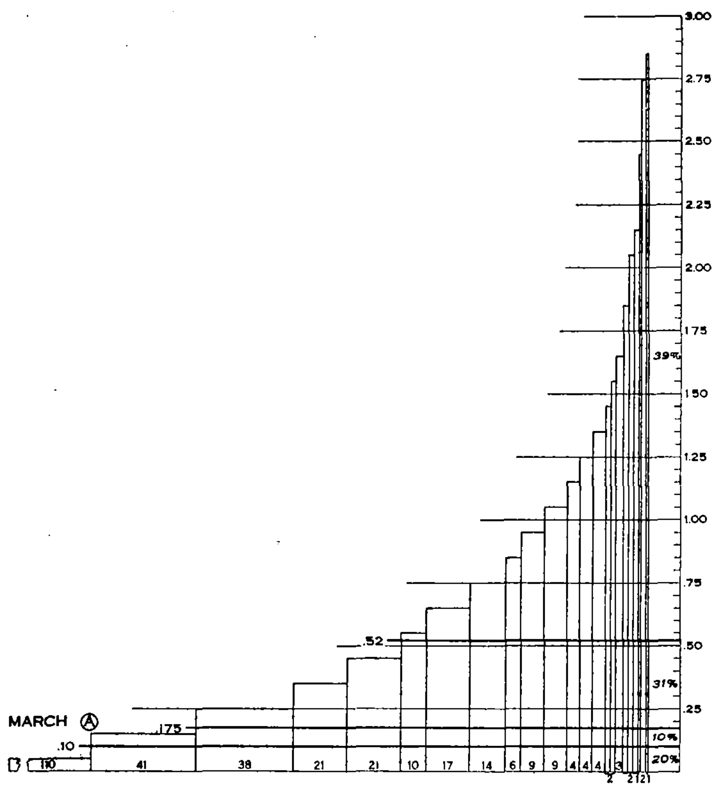
This left an amount which presumably escaped, either by transpiration or evaporation or both. It was suggested that under favorable conditions a growing crop might utilize the major part of this residue and that it might also be able to reduce the portion lost in the streams.

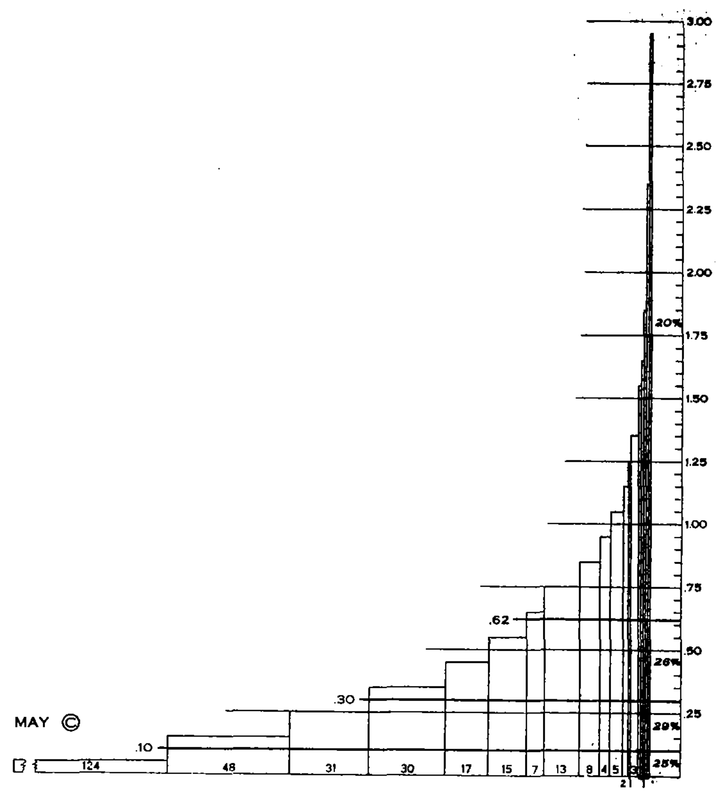
It is now proposed to try to throw a little more light on the question of effective rainfall by considering a particular case.

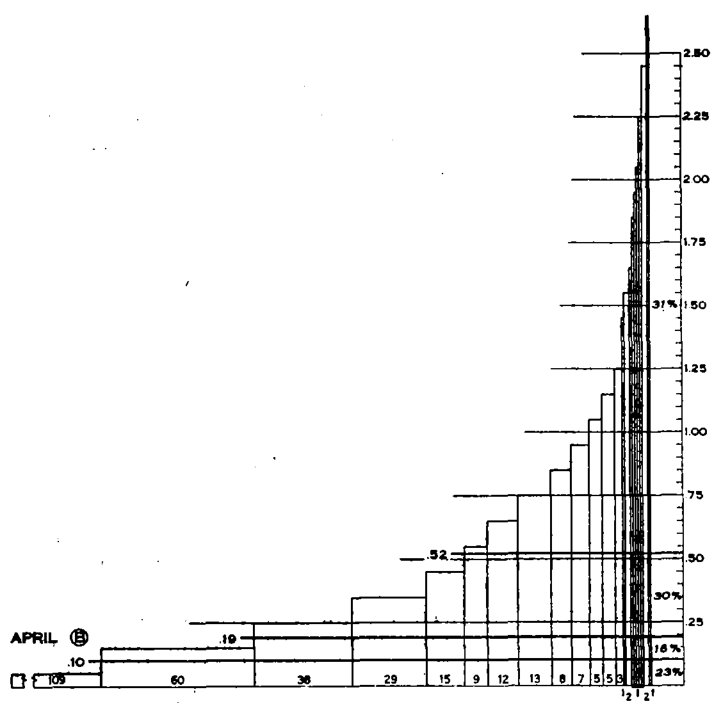
We first present the charts, A to F, showing for Knoxville for each of the months March to August, inclusive, the total number of days in the 27 years of record which have had rainfalls of the indicated amounts. The abscissæ represent days and the ordinates rainfall in inches and tenths. Each column represents the rainfall for one day and the total of the figures at the bottom gives all the rainy days for the given month for the 27 years.

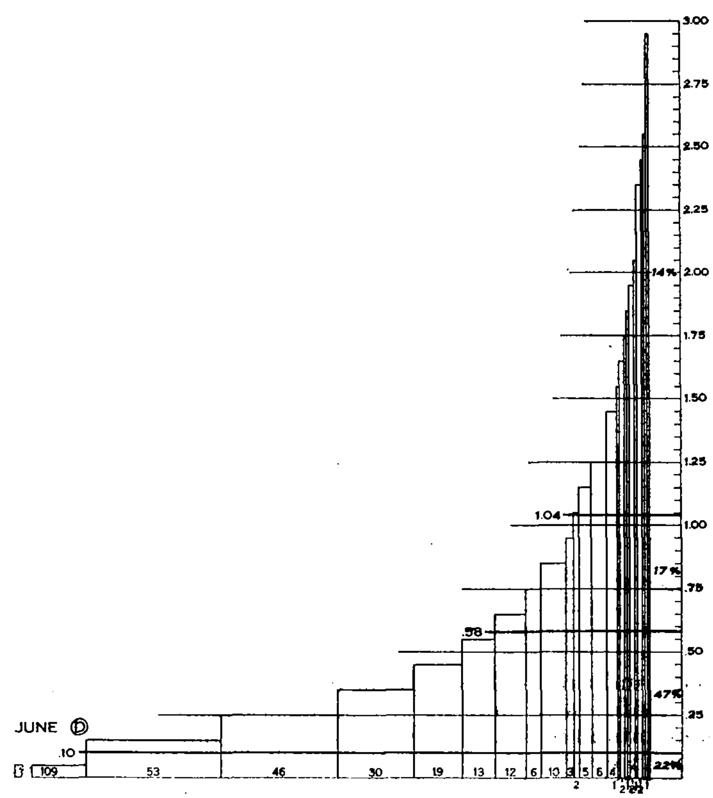
The heavy horizontal line at the 0.1-inch mark cuts off of the bottom the amount probably lost by immediate evaporation. In March this amounts to 20 per cent of the total rainfall. Then, since the previous study showed that 70 per cent of the March rainfall appeared in the river, a line was drawn at a point cutting off 30 per cent from the bottom and leaving the 70 per cent which appeared in the river above. The part between these two lines, or 10 per cent of the total, is the amount normally used in transpiration or lost later by evaporation

Next, it seemed worth while to make some distinction between surface run-off and water reaching the river by seepage. It was assumed that all water above the minimum stage of the river, for a given month, was due to

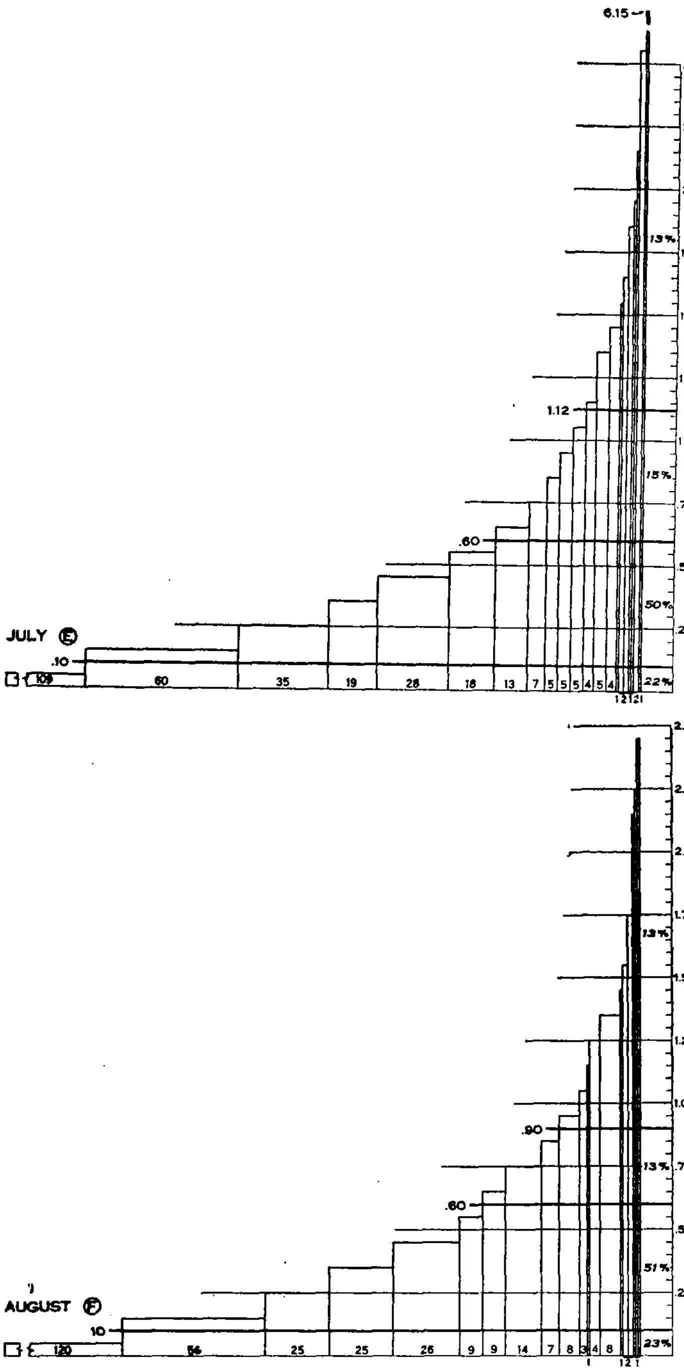

MARCH Ⓐ
.10
.175
.52
39%
31%
10%
20%
110 41 38 21 21 10 17 14 6 9 9 4 4 4 3


MAY Ⓒ
.10
.30
.62
20%
26%
29%
25%
124 48 31 30 17 15 7 13 8 4 5


APRIL Ⓑ
.10
.19
.52
31%
30%
16%
23%
109 60 38 29 15 9 12 13 8 7 5 5 3


JUNE Ⓓ
.10
.58
1.04
14%
17%
47%
22%
109 53 46 30 19 13 12 6 10 3 5 6 4

surface run-off and the rest to seepage. Using 21 years' record of rainfall, river stages, and discharge data, monthly percentages of total rainfall were obtained for seepage and surface run-off. For March these percentages were: Seepage, 31 per cent, and surface run-off, 39 per cent. Then, since surface run-off usually occurs with the heavier rains, a line was drawn cutting 39 per cent of the total rainfall off the top. This line falls at 0.52




inch, indicating that only on days having over 0.52 inch of rainfall will there be any surface run-off, and that all amounts above 0.52 inch run off. Of course, this is not true in every case, but only on the average. When the rain falls rapidly there is often surface drainage, though the total amount of precipitation may be less than 0.52 inch; on the other hand, greater amounts falling slowly, when soil moisture is depleted, may all soak in.

Table 1 shows for the months March to August the average percentage of total rainfall lost by immediate evaporation, surface run-off, seepage, and transpiration, as calculated above. Table 2 shows the daily rainfall at Knoxville, Tenn., for the months March to August, 1911.

TABLE 1.—*Average monthly percentage of total rainfall used*

| | March | April | May | June | July | August |
|---|---|---|---|---|---|---|
| Immediate evaporation | 20 | 23 | 25 | 22 | 22 | 23 |
| Transpiration | 10 | 16 | 29 | 47 | 50 | 51 |
| Seepage | 31 | 30 | 26 | 17 | 15 | 13 |
| Run-off | 39 | 31 | 20 | 14 | 13 | 13 |

TABLE 2.—*Daily rainfall, Knoxville, Tenn., 1911*

| Date | Mar. | Apr. | May | June | July | Aug. | Date | Mar. | Apr. | May | June | July | Aug. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.33 | | 0.04 | | | 0.02 | 18 | 0.11 | 0.25 | | .11 | | 0.19 |
| 2 | | | | | | 1.37 | 19 | .41 | 1.06 | | .05 | | |
| 3 | | | | | 0.18 | .01 | 20 | | T. | 0.23 | | 0.65 | |
| 4 | | 2.49 | | | .26 | T. | 21 | | .02 | .01 | | .14 | |
| 5 | .27 | .48 | | 0.04 | T. | | 22 | .21 | | .39 | .07 | | |
| 6 | .21 | | | | | | 23 | | | .22 | .01 | .03 | |
| 7 | .70 | .56 | | T. | 1.14 | | 24 | | | | .02 | 1.12 | T. |
| 8 | | .31 | | | T. | .34 | 25 | | | | .89 | | |
| 9 | .30 | | T. | | T. | | 26 | .85 | | | | | T. |
| 10 | .03 | | | | | | 27 | | .02 | | .95 | | .02 |
| 11 | | .29 | | | T. | | 28 | | T. | | .05 | | .01 |
| 12 | | .02 | | | | .64 | 29 | .29 | .06 | .22 | | | .02 |
| 13 | .26 | .24 | T. | | T. | .34 | 30 | .02 | .66 | | | .07 | |
| 14 | T. | .36 | | T. | | .02 | 31 | T. | | .12 | | .04 | |
| 15 | | .84 | | | | .01 | | | | | | | |
| 16 | | | | .30 | .68 | | Total | 4.25 | 7.64 | 1.23 | 3.32 | 5.87 | 2.99 |
| 17 | | | | .23 | | | | | | | | | |

Applying the percentages in Table 1 to the rainfall data shown in Table 2 the results shown in Figure 1 were obtained. In this diagram the portion of the rainfall represented by the total discharge of the streams is below the line $xy$, while the portion normally used by transpiration or lost by evaporation appears above that line. The areas lettered A, B, C, and D indicate the amounts disposed of in each way each month, as follows: A, immediate evaporation; B, transpiration and later evaporation; C, seepage; and D, surface run-off. Note the total of the areas marked B, 6.86 inches, which under average conditions would be divided between transpiration and evaporation.

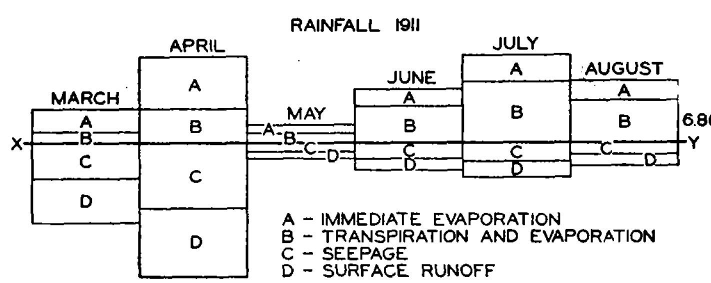



FIG. 1

Leaving this phase of the subject for the moment, we will now consider certain fields of corn that were under observation in 1911.

In that year the writer grew a few acres of corn near Knoxville, Tenn. The land was fairly good, being partly new ground, the rest having been cultivated but one year since the timber had been cut off.

The crop started off beautifully, but dry weather during May and the first half of June injured it badly and the final yield was about 18 bushels per acre. In this field the soil was broken about 6 inches deep, which is referred to as shallow tillage. My neighbors, also using shallow tillage, and on a great variety of soils, obtained practically the same results that I did. Just before the rain that came in the middle of June I observed in many of these fields the corn leaves rolled up tight and looking more like pale green spears than like corn plants.

At the University of Tennessee Experiment Station that season, there were two small fields which had been given deep tillage. The soil had been thoroughly mixed to a depth of 14 to 18 inches. The first field had been rather badly worn out and was producing about 25 bushels of corn per acre or its equivalent. Until the practice of deep tillage was begun on it in 1910 it was not so good as my field and no better than the average fields of my neighbors. In the spring of that year a cover crop of rye was turned under and in the spring of 1911 a crop of wheat and crimson clover was thoroughly incorporated with the soil by deep tillage.

For this field there was no dry spell in June that year, and it yielded 75 bushels per acre. The second field was naturally much better than the first, was treated in the same way, and produced 114 bushels per acre.

Referring again to the requirement of 250 to 400 pounds of water to produce 1 pound of dry matter in a corn plant, the larger amount being used on the poorer soil, let us assume that the poorest crop used water in the ratio of 400 to 1, the next 300 to 1, and the last or best yield 250 to 1. The 18-bushel yield would then require 3.5 inches of water, the 75-bushel yield 10 inches, and the 114-bushel yield 14 inches. The rainfall being essentially the same for all these fields, how was the third able to obtain 14 inches of water while the first was able to utilize only 3.5 inches, or one-fourth as much?

These soils would probably be classed as silt loams. When saturated they might be expected to contain in the first 3 feet not to exceed 5½ inches of water available for the use of plants. Under average conditions this amount decreases rapidly after each saturation, and under extreme conditions as much as an inch per week may be lost.

Figure 2 represents the moisture conditions for four months beginning May 1, 1911. Since April was an

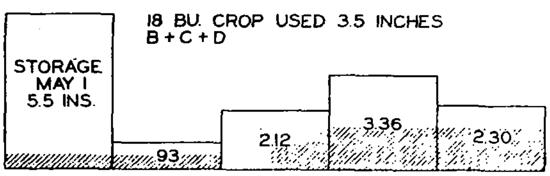



FIG. 2

unusually wet month, it is assumed that the soil contained the maximum amount of water at the end of the month or 5½ inches in the first 3 feet. Following that is shown the rainfall for each month, less the amount probably lost by immediate evaporation, as shown in Figure 1.

The diagonal shading on Figure 2 indicates the amount of water used by the 18-bushel crop. By the middle of June the corn in those fields in which the crop was suffering for water averaged about 5 feet tall. Assuming that it would take 1 inch of water to produce that much growth and noting the small amount available in May, we find that the crop drew perhaps 0.5 inch out of storage. If there had been no other losses this would leave more than 5 inches still available. As a matter of fact, however, there was practically no more available moisture in the soil, for the corn stopped growing and twisted its leaves into spears to fight off death as long as possible. From the middle of June on the supply of moisture was rather large, but the crop was not able to use it all, probably because it had been permanently injured during the previous dry weather.

In Figure 3 the diagonal shading indicates the amount of water used by the 114-bushel crop in field No. 2 at the experiment station. In constructing this figure three things have been assumed, all of which are improbable, and at least one, the last, could not possibly be true. It is assumed, first, that the surface soil has been filled with vegetable matter until it is so porous that all rainfall is absorbed at once and no surface run-off occurs; second, that the deep humus-filled soil can retain this moisture near enough to the surface for a corn plant to get it, but that during the summer none will escape by seepage; third, that the crop makes such a dense cover that there is no evaporation from the surface of the soil.

Under these assumptions all the rainfall after the crop is well started is available for plant growth except the amount which evaporates immediately after each rain (represented by A in Figure 1 but omitted from Figure 3). Even with these extravagant assumptions, only 8½ inches of water were available after May 1, while the crop used 14 inches. It must then have drawn 5½ inches from storage. We say, however, that 5½ inches was the maximum amount that this soil could be expected to hold in the first 3 feet, so that, under the im-

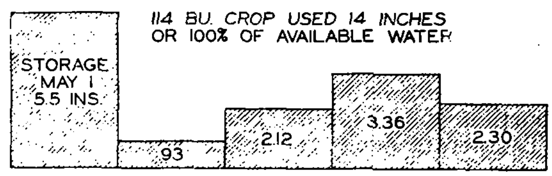



FIG. 3

probable conditions assumed, the crop has used every drop of water available. As a matter of fact the corn probably went deeper than 3 feet for part of its water supply, for it is unthinkable that there would be no evaporation from the surface from May 1 to August 31 when these dates included one rainless period of 18 days and another of 23 days with practically no rain.

The 114-bushel crop was 100 per cent efficient in utilizing available water, while the 18-bushel crop was only 25 per cent efficient. Why?

Let us now consider the soil for a few moments, looking upon it as a laboratory, or perhaps better, as a factory. Five things are necessary for an efficient factory—material, power, machinery, workers, and favorable working conditions.

In our factory the problem of materials is a very simple one. Our materials are air, water, and minerals. The air is free and abundant. The water also, as material to be chemically combined in the solid matter of the plant, is free and abundant; a 100-bushel crop would require perhaps 0.04 of an inch of water. The mineral material, if deficient in the soil, can always be supplied at no great expense.

Our power problem is also taken care of for us, as we depend entirely upon heat received from the sun for the energy that makes our crops grow.

The machinery of our factory is water. It carries the materials dissolved in the soil up into the leaves for digestion and elaboration and thence throughout the plant to build tissue. The quantity of water employed as machinery is probably three hundred times that used as material, and it is here that deficiencies are likely to occur. A crop of 100 bushels of corn per acre will probably require at least 12 inches of water. In the more humid climates a greater amount than this is usually received during the growing season of corn, but the supply is irregular and there are often periods of deficiency of available water. Except where irrigation is possible, the quantity received and the time of its receipt are wholly beyond our control.

The worker in our factory is life, in the plant itself and in the soil bacteria that prepare food for the plant. We can in some cases inoculate the soil with the right kind of bacteria, but beyond that point we are helpless except as we come to the fifth requirement for a factory, namely, favorable working conditions.

Here our opportunity for effective work begins—and ends. We have free material, free power, free machinery, free workers, and the only thing we can do to increase production to any great extent is to improve the working conditions in the soil Ideal conditions would include an optimum supply of water, a well-aerated soil, plenty of food materials, and sufficient heat. It would seem, if we may judge by results, that in the field producing 114 bushels per acre these conditions had been met as far as was humanly possible.

Two things were done in this field that were not done in the 18-bushel field. The soil was stirred to a greater depth and a very large amount of vegetable matter was added. Other experiments have shown that deep tillage without extra vegetable matter is of little or no value, so that the increased yield in this case must have been due to one of two things. Either the abundant supply of humus was entirely responsible, or, in combination with deep tillage, it furnished conditions favoring the highest possible conservation of the water supply, thus stimulating the living workers to maximum activity. Whether or not the deep tillage was of any value remains to be determined by further experiment.

Finally, it appears that effective rainfall is not a function of total rainfall (except when the latter is the limiting factor), but depends entirely upon the condition of the soil and the capacity of the crop for utilizing water. If one were to offer a practical suggestion based on this study it would be this: The addition of what would ordinarily be considered an excessive amount of vegetable matter to the soil might be a very profitable farm practice.

## THE WEATHER INFLUENCE ON CROP PRODUCTION IN REGIONS OF SCANTY RAINFALL

551.578.1 : 633

By W. A. MATTICE

[Weather Bureau, Washington]

In recent years the surplus of Temperate Zone humid lands suitable for economical cropping has become so small that the possibilities of cropping in semiarid lands have been increasingly studied. Under existing farming practices, the world's food crops are produced on a very small portion of the land. These lie principally in the North Temperate Zone, yet in the Northern Hemisphere outside the Tropics more than three-fourths of the land has an annual rainfall too scanty to permit of successful farming by ordinary methods.

Under such conditions rainfall has a significance not attained in humid regions, because of the fact that at best the moisture present is rarely of a some-to-spare quantity, and what may be termed an average year has barely enough for crops to thrive.

A recent Department of Agriculture Bulletin, No. 1304,[1] entitled "Crop rotation and cultural methods at the Akron, Colo., Field Station," prepared by the Office of Dry-Land Investigations, Bureau of Plant Industry, contains much valuable information relative to crop production in that typical semiarid section of the United States, and a study of the data contained in it brings out many interesting facts as to the weather influence on yields.

In dry-land farming the retention of moisture in the soil is of primary importance, and consequently the relative humidity and the closely associated phenomena of evaporation afford a good index for studying the general effects of weather on crops. Statistical correlations show also that, so far as rainfall is concerned, the amount received during critical periods of growth for the several crops is of much greater importance than the annual amount, notwithstanding a statement in the bulletin above referred to that the greatest single factor in crop production is the amount of annual precipitation. Correlations show that several other factors give much higher coefficients than the annual amount of precipitation.

The minimum amount of precipitation necessary for successful farming by ordinary methods is generally agreed to be between 15 and 20 inches. The Akron station has an average annual amount of 17.95 inches, but this is an average based on only 15 years. More than half of the years had less than this, sometimes reaching as low as 13.44 inches. Although the seasonal distribution of precipitation is in general more or less favorable for crop production, there were years when the amount of moisture received was insufficient to maintain plant growth, and 67 per cent of them had precipitation below normal.

There also occur in this region rather brief droughts which would not appear in a table of monthly totals. While the damage caused by these is difficult to determine and the length of time plants can successfully resist them problematical, their injurious effect is sufficient to aggravate materially the results of the generally scanty moisture supply.

The significance of the evaporation is also difficult to determine quantitatively, but it appears probable that about 1 inch of rainfall is required to offset the effect of 5 or 6 inches of free water-surface evaporation. Griffith Taylor, of the University of Sydney, Australia, found that about 5 inches of evaporation was equivalent to 1 inch of rainfall in Australia (*1*). If this ratio holds true for the United States, the effective rainfall for the summer at Akron, because of the relatively high rate of evaporation, is reduced on the average to about 5 inches.

The Akron, Colo., field station was established in 1907 and the first crops were grown in 1908; the rotations were begun in 1909. The soil at the station is typical of the so-called hard land of that region, and the climate conforms to the general conditions prevailing in the drier parts of the surrounding Great Plains.

Precipitation for the 16 years of record averaged 17.95 inches annually, with an average April to September rainfall of 13.69 inches. The latter is about 76 per cent of the annual, with the greatest monthly amounts occurring from April to August. The temperature is

[1] This bulletin deals entirely with the difference in yields under the various cultural methods and merely touches on the weather effect. The yield data from this bulletin serve as a basis for the correlation studies herein presented.